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Optical and infrared investigation towards the $z = 3.8$ quasar pair PC1643+4631 A & B

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ABSTRACT

In a companion paper (Paper I: Jones et al. 1996) we report the discovery of a cosmic microwave background decrement, indicative of a distant cluster with mass $\sim 10^{15} M_{\odot}$, towards the quasar pair PC1643+4631 A & B ($z = 3.79, 3.83$, separation $198''$). To search for the cluster responsible, we have obtained R -, J - and K -band images of the field and have also carried out optical spectroscopy of selected objects in it. No such cluster is evident in these images. Assuming the cluster causing the decrement is similar to massive clusters already known, our magnitude limits imply that it must lie about or beyond $z = 1$. This provides independent support for the X-ray-based distance argument of Paper I. The cluster must gravitationally lens objects behind it; for a cluster z around $1 - 2$, the Einstein-ring radius for sources at $z \approx 3.8$ is $\sim 100''$. Simple modelling, producing simultaneously the S-Z effect and the lensing, shows that the source positions of quasars A and B lie within $\sim 10''$ of each other and may indeed be coincident. The two quasar spectra are found to be remarkably similar apart from their one-percent redshift difference. Assuming A and B are images of a single quasar, we present a possible explanation of this difference.

Subject headings: Cosmic microwave background—gravitational lensing—
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1. Introduction

In a companion paper (Paper I: Jones et al. 1996), we report the discovery with the Ryle Telescope (RT) of a cosmic-microwave-background (CMB) decrement towards the $z \approx 3.8$ quasar pair PC 1643+4631 A & B. We argue there that the decrement is most likely to be due to the Sunyaev-Zel’dovich (S-Z) effect caused by a system with mass $\sim 10^{15} M_{\odot}$ but lying beyond the range of X-ray telescopes.

To further constrain the nature and distance of the system causing the CMB decrement, we have carried out R -, J - and K -band imaging of the field with the optical 4.2-m WHT (William Herschel Telescope, La Palma, Canary Islands) and the 3.8-m UKIRT (UK Infrared Telescope, Hawaii). In addition, we have used the WHT to obtain spectrophotometry of quasars A & B at higher sensitivity and resolution than previously reported because, as it proceeded, our investigation increasingly pointed to the possibility that quasars A & B are physically related.

2. Optical and Infrared Observations

All observations were carried out in the period 1995 June to August, all in photometric conditions and with a maximum airmass of 1.3. The imaging is described first and then the spectrophotometry. We take $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega = 1$ and $\Lambda = 0$.

J - and K -band images were obtained with the UKIRT IRCAM3 camera, on a scale of $0''.29 \text{ pixel}^{-1}$. For R -band imaging we used the Tek 1024 CCD mounted on the Auxilliary Port of the WHT, giving $0''.22 \text{ pixel}^{-1}$ after binning. In each case the useful field size was $\approx 120'' \times 120''$. Therefore, in order to cover as big a region around the decrement as practicable, we observed in each band the seven fields whose centres are given in Table 1. Individual J and K frames of each field were dithered in a 3×3 grid with $12''$ steps to avoid repeating bad pixels. Consecutive grids were offset by $2''$. For each of fields 0–6, the total integration time was 27 min in J and 45 min in K . The infrared seeing was $1\text{--}1''.5$ FWHM, but telescope judder elongated the images to $2''$ FWHM. In R , a 5-min integration time was used for each of fields 1–6 and 10 min for field 0; seeing was $1''.5$ FWHM. Images of photometric standard stars were taken throughout.

The optical and infrared images were bias-subtracted, flat-fielded and flux-calibrated using standard procedures in IRAF. The limiting magnitudes for point sources ($3\text{-}\sigma$ within $1''.5$ radius) are as follows: for field 0, $R = 24.5$, $J = 22.2$, $K = 20.6$; for fields 1–6, $R = 24.2$, $J = 22.2$, $K = 20.6$.

Optical spectrophotometry was carried out at the WHT using the red and blue arms of the ISIS spectrograph simultaneously. With gratings of 158 line mm^{-1} and Tek CCDs, we obtained continuous coverage from 3500 \AA to 8500 \AA and a spectral resolution of 12-\AA FWHM. A $2''$ -wide slit was used with typical seeing $0''.9\text{--}1''.2$ FWHM. Exposures of spectrophotometric standards were taken routinely. In this way, spectra were obtained for quasars A and B, each with an integration time of 25 min, and also for objects close to the decrement centre, typically with 10–15 min exposures. Bias subtraction, flat-fielding and flux calibration were done using IRAF.

3. Analysis of the Field

To search for a candidate cluster, we classified objects in the field by colour. We measured magnitudes (integrated over a $3''$ -radius aperture) for all objects detected in K in the seven fields, except for stars and bright galaxies which were obviously nearby. Fig. 1 shows the composite K image. All objects with $K \leq 19.5$ (the $3\text{-}\sigma$ photometry limit is $K = 19.9$) are marked with a colour-dependent symbol, except for very bright objects and objects at the extreme periphery of the composite. The form of the symbol is governed by the redness ($R - K$) of the object. A cross is added if $(J - K) > 2$, perhaps indicative of a high-redshift elliptical (e.g. Bruzual & Charlot 1993).

The immediate result is that in these deep images no cluster capable of causing the decrement is evident. We do see red galaxies with $(J - K) > 2$ both around quasar A and in the southern part of the composite, including the red galaxies found by Hu & Ridgway (1994). If these galaxies with $K < 19$ lie at $z \gtrsim 2$, as their colours suggest, they would be as luminous as the brightest galaxies in low-redshift clusters (Aragón-Salamanca et al. 1993), i.e. have luminosities greater than a few L_* . A band of objects can also be seen across the field, mostly with $2.5 < (R - K) < 3.5$. We obtained spectra for some of these: the four objects marked “S” on Fig. 1 turned out to be stars; object 1 ($K = 17.0$) is an emission-line galaxy with strong $[\text{O II}] \lambda 3727$ and $\text{H-}\beta$ at $z = 0.659 \pm 0.002$; objects 2 and 3 are companion galaxies with $[\text{O II}]$ emission at $z = 0.670 \pm 0.002$ (object 2 is not detected in J or K but has $R = 22.2$; object 3 has $K = 17.4$).

We reiterate that these observations do *not* reveal evidence of a cluster near the decrement position, implying the cluster is distant. From our knowledge of the cluster luminosity function at $0.5 < z < 1$ (e.g. Aragón-Salamanca et al. 1993), a cluster at, for example, $z = 0.7$ should have a brightest member of $K \approx 16.2$ and several tens of members present brighter than $K = 19$. This is clearly not observed — recall our $3\text{-}\sigma$ photometry limit over a $3''$ -radius aperture is $K = 19.9$. Following this argument, our images imply that

any “normal”, S-Z-producing cluster must lie at about $z = 1$ or beyond. This is consistent with the X-ray result of Paper I. The existence of a significant population of such clusters is not favoured by current “bottom-up” models of structure formation (e.g. cold dark matter, see e.g. Peebles 1993).

Of course, one can speculate that the cluster is, compared with known clusters, underluminous in X-rays because the electron density, n , is low, and underluminous in the optical/infrared because its galaxies have burned out (see Silk 1986) or little star formation has occurred in it. However, to produce an S-Z signal, the line-of-sight pressure integral $\int nTdl$ must be maintained, so a system with mass $\sim 10^{15}M_{\odot}$ is *still* required.

4. The System as a Gravitational Lens

Given that a massive system must lie in the direction of the decrement, gravitational lensing will occur. Moreover, if the system lies at $z < 3.8$ it will affect the apparent (“object”) positions of quasars A & B. To investigate the unlensed (“source”) positions of A & B, we have carried out simple modelling subject to the additional constraint that the lens gas causes an S-Z effect of the observed magnitude (see Paper I). We employed the lensing formulation of Blandford & Narayan (1992) and a standard spherically-symmetric “ β -model” to describe the S-Z-producing gas. In this model the density is given by $n = n_0\{1 + (\theta/\theta_C)^2\}^{-1.5\beta}$, where θ_C is the core-radius (see e.g. Cavaliere & Fusco-Femiano 1976). We have assumed $\beta = 0.67$ and a temperature of 5×10^7 K, both typical of known X-ray clusters. As a first approximation, we placed the lensing mass at $z = 1$, adopted a ratio of total mass to gas mass of 10:1, and made the lens and S-Z centres coincident.

By adjusting the values of θ_C and n_0 , we determined the source positions as a function of cluster gas distribution. Intriguingly, a distribution with $\theta_C = 35''$ (300 kpc) and $n_0 = 7 \times 10^3 \text{ m}^{-3}$ both produces the S-Z decrement observed with the RT and makes the source positions of quasars A & B *almost coincident* (within $10''$). The Einstein-ring radius is $100''$ and the total mass, including dark matter, within a 1-Mpc radius of the centre is $1.2 \times 10^{15}M_{\odot}$.

It is remarkable that these values of core radius and mass are completely typical of known luminous clusters. The values are not particularly sensitive to β or T , nor to the redshift of the lens (the mass required changes by less than fifty percent for $0.6 < z < 3$). In other words, $\int nTdl$ is fixed by the S-Z decrement, and if one takes gas parameters similar to those of known clusters, the gravitational-lensing effects are such that the source positions of A & B must be close together. Of course, minor adjustments to the assumed

lens potential could make the quasar source positions coincide exactly. Then quasars A & B would be double images of the same object. This would be by far the largest-separation multiple-image known. At least one other image would be expected but it could easily be fainter than our current magnitude limits.

The possibility that quasars A & B are the same object compelled us to compare their spectra as closely as possible. The WHT spectra we obtained for quasars A & B (see Fig. 2) have higher spectral resolution and sensitivity and extend further into the blue than those published by Schneider et al. (1991). We confirm their broad-line redshifts and damped Ly- α absorption at $z = 3.14$ in the spectrum of quasar A. The continuum shapes, line strengths and widths are similar in both quasars and two additional features in common are particularly striking. First, narrow absorption is clearly present in both objects, in both Ly α $\lambda 1216$ and C IV $\lambda\lambda 1549, 1551$, shifted in both spectra $\sim 6000 \text{ km s}^{-1}$ to the blue of the line peaks. Second, abrupt Lyman-limit absorption is seen in the light from both quasars at the same redshifts as the narrow absorption features. Associated Lyman-limit systems are seen in about 20% of quasars with $z > 2.5$ selected for absorption-line studies (Lanzetta 1991; Storrie-Lombardi et al. 1994), although the probability of detecting two systems with similar relative velocities is much smaller. For intervening systems, a comoving number density of 0.06 Lyman-limit absorbers per line of sight is expected within a redshift interval of 0.02 at $z = 3.8$ (Storrie-Lombardi et al. 1994). We note that associated Lyman-limit systems will follow a different redshift distribution if they are affected directly by the quasar environment, which is likely.

However, despite the qualitative similarity of spectral features and gaseous environments, the redshift difference between quasars A & B remains significant. We find the redshifts of the broad emission lines in quasars A & B to differ by $(3.0 \pm 0.5) \times 10^3 \text{ km s}^{-1}$, with a similar difference for the Lyman-continuum and narrow C IV absorption, and find a difference in narrow Ly α absorption of $(3.0 \pm 0.3) \times 10^3 \text{ km s}^{-1}$.

For quasars A & B to be two gravitationally-lensed images of one source, their one-percent redshift difference has to be explained by intrinsic spectral changes occurring over the likely delay between the two lightpaths, $\sim 10^3$ years. We note that velocity shifts, comparable with those observed between quasars A & B, have been observed between high- and low- ionisation emission lines in numerous quasar spectra and interpreted as evidence for radial velocities within the broad-line region (BLR) (see Gaskell 1982; Wilkes 1986). Such a radial, or bulk, velocity that changes over $\sim 10^3$ years would provide an explanation for the velocity differences of quasars A & B; it is reassuring that the bulk-velocity changes of 3000 km s^{-1} are less than the random spread (Ly α and C IV have FWZI of $(21 \pm 3) \times 10^3$ and $(12 \pm 2) \times 10^3 \text{ km s}^{-1}$, respectively).

A model involving a disk (perhaps warped and twisting due to an interaction) and outflow together with the effects of shielding can explain the velocity differences *provided* the shifts of the narrow absorption features are tied to the shifts of the broad emission lines. This amounts to a requirement that the absorbing gas lies in or immediately adjacent to the BLR, rather than at kpc-scale distances in the narrow emission-line region (NLR). We next argue that this is plausible.

The large optical depth ($\tau > 4$) in the Lyman-limit absorption trough suggests that both quasars are viewed through a neutral hydrogen column of at least 10^{21} m^{-2} (e.g. Sargent 1988). Furthermore, the measured equivalent width⁵ of the strongest absorption feature in the $\text{Ly}\alpha$ emission line, $W_\lambda = 20 \pm 3 \text{ \AA}$ in quasar A ($13 \pm 2 \text{ \AA}$ in quasar B), corresponds to a range of column densities $10^{24} < N_{\text{H I}} < 10^{27} \text{ m}^{-2}$ using a curve-of-growth analysis (e.g. Spitzer 1978). Taking a representative BLR density of $n_{\text{H II}} \sim 10^{15} \text{ m}^{-3}$ (e.g. Osterbrock 1993), assuming the neutral hydrogen has the same temperature as the BLR and is in pressure balance with it and has a filling factor of 10^{-3} , these column densities correspond to line-of-sight distances of 10^{11} – 10^{15} m , i.e. much less than a parsec. Taking a spherical geometry, the corresponding upper limit for the H I mass is $\sim 0.01 M_\odot$. These parameters suggest the amount of material needed to absorb $\text{Ly}\alpha$ in the quasar is easily containable within the BLR.

A critical test of the notion that the spectra of A & B are of the same quasar seen at different times would be to see if narrow lines such as $[\text{O III}] \lambda 5007$ (in the infrared) lie at the same redshift in both spectra; such lines from the large NLR will not vary over $\sim 10^3$ years.

5. Conclusions

(1) R -, J - and K - imaging of the field around PC 1643+4631 A & B has not revealed a cluster in the direction of the CMB decrement. Therefore, if the $10^{15} M_\odot$ cluster producing the decrement is similar to known massive clusters, it must lie at about $z = 1$ or beyond. This is consistent with the X-ray-based argument of Paper I.

(2) If the system causing the decrement lies significantly nearer than $z = 1$, it must contain far fewer luminous galaxies than the nearer clusters known to cause S-Z effects. It must also be larger, hotter and more rarefied than known clusters in order to give a lower

⁵The relative strength of these absorption lines is affected by additional uncertainties due to the complex absorption in the blue wing of the $\text{Ly}\alpha$ emission.

$\int n^2 dl$ (and hence lower X-ray luminosity) and yet give the observed S-Z decrement.

(3) If the massive 1643+4631 system is a member of a significant population, then neither the higher- z picture in (1) nor the lower- z picture in (2) appears consistent with current cold-dark-matter theories of cluster formation.

(4) Whether (1) or (2) applies, the $10^{15} M_{\odot}$ required to produce the decrement must gravitationally lens background objects. Assuming the mass lies in front of the quasars, simple modelling, producing simultaneously the S-Z effect and lensing, shows that the source positions lie within $10''$ of each other.

(5) A slight adjustment to the assumed lens potential would make the quasar source positions coincide. If A & B are two images of one quasar, then the one-percent difference in broad-emission and narrow-absorption velocities, in otherwise very similar spectra, has to be explained. We have argued that this is possible given (a) the expected $\sim 10^3$ year difference in light travel time along the two paths, and (b) a system with a changing systematic velocity component in which narrow-line absorption takes place in the same region as the broad-line emission; we have shown that the mass and size of the required absorption region are small enough that this is plausible.

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Table 1: Optical/Infrared Field Centres

Field	RA (B1950)	Dec	Comments
0	16 43 42.7	+46 30 49	Central field
1	16 43 41.6	+46 29 39	
2	16 43 46.0	+46 28 24	
3	16 43 48.7	+46 29 39	
4	16 43 35.3	+46 31 23	includes quasar A
5	16 43 50.4	+46 30 55	includes quasar B
6	16 43 45.0	+46 32 00	

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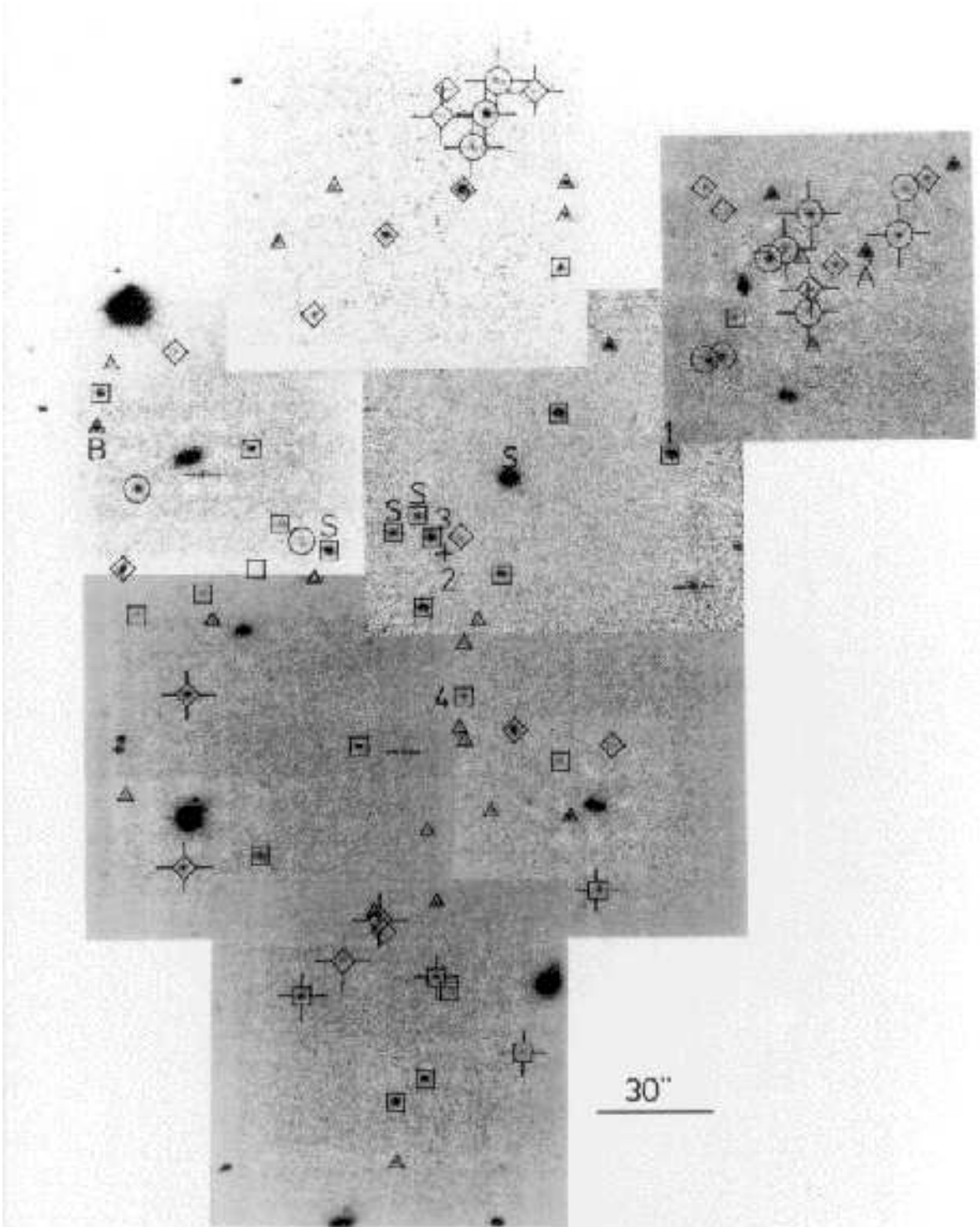


Fig. 1.— Mosaic of infrared K -band images of fields 0–6 (see text). Objects with $K \leq 19.5$ have been assigned colour-dependent symbols. The following $R - K$ ranges are marked: 0.0–2.4 by \triangle , 2.5–3.4 by \square , 3.5–4.4 by \diamond , > 4.5 by \circ . A cross is superposed if $J - K > 2.0$. Objects marked with two horizontal bars have $K > 19.5$ but no colour information. Spectroscopic identifications are also shown for a number of objects: quasars “A” & “B”; stars “S”; galaxies “1”, “2” & “3” (see text). The centre of the S-Z decrement lies near object “4”; note that the positional accuracy of the decrement centre is $\approx 20'' \times 30''$ (see Paper I). The different apparent background levels between the fields reflect small variations in sky noise between

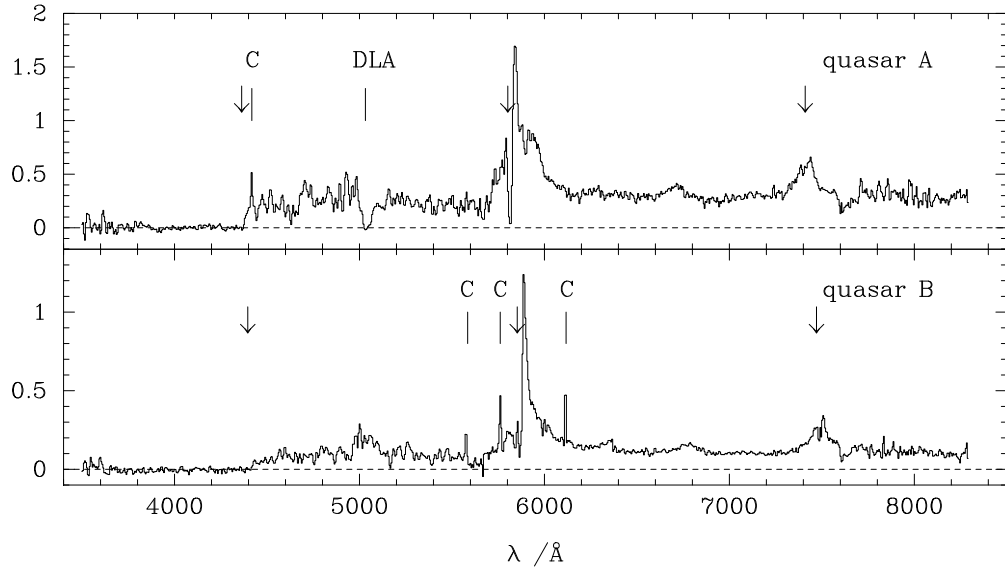


Fig. 2.— WHT spectra for quasars A and B. The ordinate scales are $f_{\lambda}/10^{-19} \text{ W m}^{-2} \text{ \AA}^{-1}$. Cosmic rays are marked “C”; night sky affects the spectra at 7600 \AA and to the red. Associated absorption features are marked in both spectra with vertical arrows, including Lyman-limit, Ly α and C IV absorption. The spectrum of quasar A also shows damped Lyman- α (DLA) absorption at 5032 \AA .